

## MECHANICS OF REMORA REMOVAL BY DOLPHIN SPINNING

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Spinner dolphins (*Stenella longirostris*) are subjected to the attachment of remoras (Hester *et al.* 1963, Norris and Dohl 1980, Fertl and Landry 1999). The remoras (family Echeneididae, including the sharksucker [*Echeneis naucrates*] and the whale-sucker [*Remora australis*]) use a specifically adapted suction disk (Fig. 1) to attach to cetaceans, sharks and other large pelagic animals (Fertl and Landry 1999, O'Toole 2002, Ritter 2002, Brunnschweiler and Sazima 2006, Silva and Sazima 2006). This attachment irritates the skin of the host (Palmer and Weddell 1964; Schwartz 1977, 1992; Ridgway and Carder 1990) and adds to the resistance of swimming. The high energy demands of rapid swimming require minimization of the resistive forces (drag) over the bodies of animals like dolphins (Weihs and Webb 1983, Fish 1993). For dolphins then, remoras effectively become hydrodynamic parasites. Removal of remoras is, thus, likely important to maintain unencumbered swimming performance.

Hester *et al.* (1963) first suggested that aerial maneuvers executed by spinner dolphins (*Stenella longirostris*) were used in the removal of remoras. This aerial behavior is characterized by rotation around the longitudinal axis of the body as the dolphin leaps from the water (Hester *et al.* 1963, Norris and Dohl 1980, Leatherwood *et al.* 1988, Norris *et al.* 1994). The dolphin may spin up to seven times in the air and reach heights of 3 m before subsequently striking the water surface broadside.

A recent computational model indicated that the aerial spinning and water reentry could generate sufficient force to dislodge an attached remora from spinner dolphins (Fish *et al.* 2006). The centrifugal effect of the aerial spin causes the unattached body of the remora to be thrown out radially (Fig. 2). The combined vertical velocity

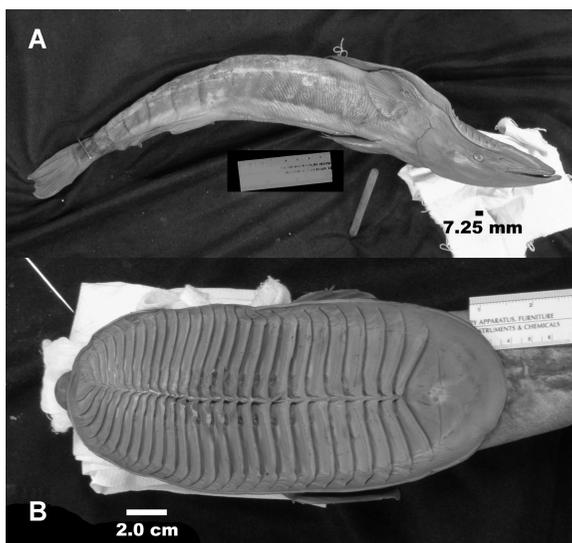


Figure 1. A specimen of a whalesucker (*Remora australis*) from the Harvard Museum of Comparative Zoology (MCZ23247). Photographs show (A) lateral view of whalesucker and (B) close-up of suction disk with transverse laminae.

from the fall of the dolphin and tangential velocity of the spin generate a force on the remora at impact that can be as high as approximately 700 times the weight of the fish. That force is generated from the lateral drag on the radially oriented remora. Dislodgement is inferred to occur because of lateral shearing on the suction disk. Transverse rows of modified spines (laminae) on the suction disk are erected to increase friction with the skin of the host (Moyle and Cech 1988, Fulcher and Motta 2006). On the compliant skin of the dolphin, the spines would tend to dig into the skin as the drag on the remora increases longitudinally with the swimming speed of the dolphin. Thus, it is expected that less force would be required to dislodge the remora by shearing than a longitudinally oriented force (Fish *et al.* 2006).

The model that is proposed in this communication examines the mechanics of dislodgement due to shear stresses and centrifugal forces experienced by the remora attached to a spinning dolphin. This model is an extension of the model initially proposed in Fish *et al.* (2006), which did not consider the direct influence of the centrifugal and shear forces necessary for remora dislodgement.

#### THE MODEL

The present model of remora detachment is based on two separate mechanisms acting consecutively.

First, during the aerial phase, the centrifugal force produced by the rapid spinning of the dolphin causes the remora, which is attached to the host's skin, to be thrown radially outward. This force acts at the center of mass (CM) of the remora, which is posterior to the suction disk, so that the centrifugal force produces a moment that acts to peel the remora off, tail first. This effect produces a high stress on the rearmost edge of the disk, forcing an initially small separation that permits pressure



*Figure 2.* Leaping aerial spin by spinner dolphin (*Stenella longirostris*). Attached remora is shown on underside of head. The close-up shows that the remora's body posterior of the suction disk is oriented radially due to dolphin's spin. Remoras are an irritant to dolphins as displayed by the open sore from the suction disk. Photograph courtesy of Robert Pitman (NOAA/NMFS).

equilibration and a significant reduction of the disk-holding force. This is enough to start peeling the remora off but may still be too short in duration to cause full separation in itself.

Second, if the dolphin's return to water is broadside, as usually observed (Hester *et al.* 1963, Norris and Dohl 1980), the remora will suffer a strong impact due to the water drag, which acts in a lateral direction relative to the disk and its laminae. This drag will help dislodge the remora sideways (Fish *et al.* 2006). In addition, the impact has a disorienting effect on the remora, allowing the dolphin to distance itself from the remora after it is dislodged.

#### ANALYSIS

A remora will detach radially outward if the centrifugal force  $F_c$  (Fig. 3) is equal to or larger than the detachment force, *i.e.*,

$$F_c = m \omega_d^2 R \geq F_d, \quad (1)$$

where  $\omega_d$  is the rate of rotation of the dolphin (and thus, of the remora's center of mass,) in rad/s, the subscript  $d$  indicates the speed at which detachment occurs,  $R$  is the radial distance of the attached remora's CM from the dolphin's axis of rotation, and  $F_d$  is the force required for detachment of the remora.

Three examples are used to evaluate the model. Using data for spinner dolphins and remoras (Fish *et al.* 2006, Fulcher and Motta 2006), we define a set of nominal remora dimensions for the analysis as: length (Fulcher and Motta<sup>1</sup>)  $L = 0.3$  m, mass  $m = 0.1$  kg, location of CM at  $0.4 L$ , and disk length  $0.08$  m starting  $0.02$  m from the anterior end (Fig. 3).  $F_d$  is  $10$ – $20$  N, based on a remora adhering to Perspex and sharkskin, respectively, and the pressure differential under the remora disk =  $20$  kPa (Fulcher and Motta 2006). The nominal dolphin body radius is  $0.10$  m. The remora's CM is  $0.01$  m further out from the dolphin, as the remora itself has a thickness of about  $0.02$  m.

<sup>1</sup> Personal observation from B.A. Fulcher and P. J. Motta, University of South Florida, February 2005.

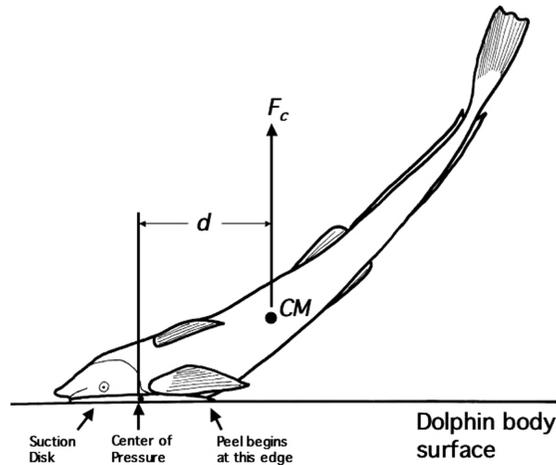


Figure 3. Position of centrifugal force,  $F_c$ , with respect to center of mass, CM, of the remora and center of pressure of the suction disk. The value  $d$  is the distance between CM and the center of pressure.

The CM of the remora is moved out by another 0.03 m due to the outward force (Fig. 3, 4), so that  $R = 0.14$  m in equation (1). We neglect the possible small changes in longitudinal CM location resulting from the radial displacement of the posterior portion of the remora. For Perspex,  $\omega_d = 26.7$  rad/s and for sharkskin,  $\omega_d = 37.7$  rad/s. These speeds correspond to rotation at 4.25 Hz and 6.0 Hz, respectively, which are faster than observed rotations by spinner dolphins, which have an upper limit of 3 Hz (Fish *et al.* 2006). Actually, many of the remoras are larger than the ones measured by Fulcher and Motta (2006).

In the second example of a sharksucker studied by Townsend (1915), the length was 2.1 times the nominal and the force was 107.9 N. Assuming allometric growth, the  $R = 0.10 + 0.02 + 0.06 = 0.18$  m, and the remora mass is 0.92 kg. For such a large remora, the dolphin rotation rate for detachment is 4.0 Hz for a relatively smooth surface. A third example is the whalesucker. The specimen shown in Figure 1 has a total length of 48.7 cm, (1.62 time the nominal length) and mass of 0.8 kg. This specimen has a much thicker body (0.07 m max thickness, *i.e.*, about 3.3 times nominal) and CM about 0.02 m anterior to the rear end of the suction disk. For a rotation rate of 3 Hz, a detaching force of 32.6 N is obtained for this individual.

The forces on the suction disk in the detachment process, however, are larger than the estimates above due to an additional mechanism. As mentioned previously, the centrifugal force acts at CM of the remora, causing a moment tending to lift the rear end of the disk off the host's skin. The magnitude of this moment  $M$  is a product of the centrifugal force and the distance between CM of the remora and the center of pressure of the suction disk ( $d$ ) (Fig. 3):

$$M = F_c d = m \omega_d^2 R d. \quad (2)$$

The remora's CM moves farther from the host's body during the spin, increasing  $F_c$  and the resulting moment. CM also moves closer to the center of pressure. This

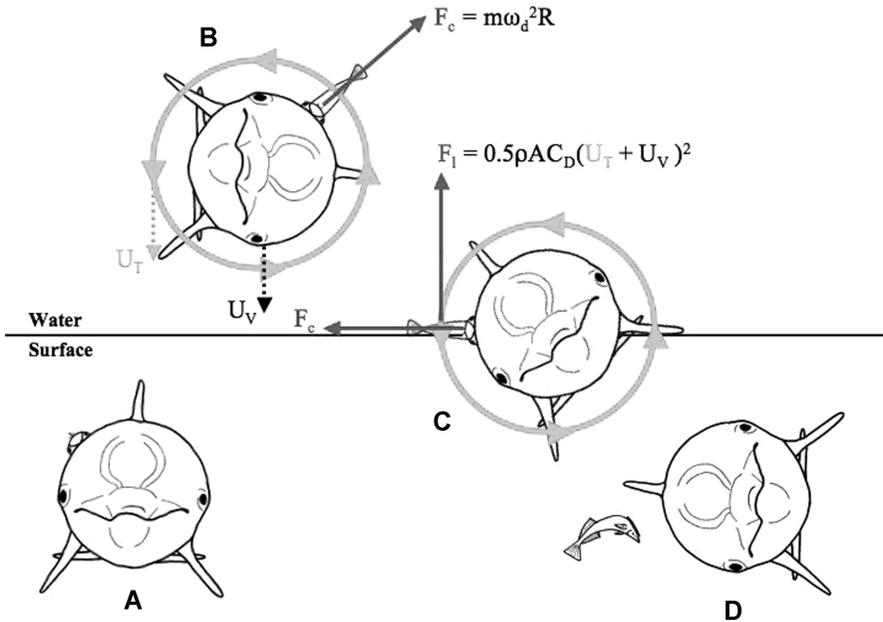


Figure 4. Forces and stages (A to D) of remora detachment from spinner dolphin. The blue line represents the water surface. (A) Submerged swimming dolphin with attached remora. (B) Dolphin has performed a spinning leap. Green circle indicates spin and direction. Unattached body of remora is oriented radially due to centrifugal force,  $F_c$ . The remora experiences a tangential velocity  $U_T$ , from the spin and a vertical velocity,  $U_v$ , from the leap. (C) Dolphin and remora impact water surface. Remora experiences a large lateral force,  $F_l$ , due to the water impact. (D) Forces combine to detach remora from dolphin.

action tends to decrease  $d$ . Thus in our analysis, the moment is assumed to remain constant. For our nominal case  $d = 0.06$  m with a spin-rate of 18.9 rad/s (3 Hz),  $M = (0.1)(18.9^2)(0.14)(0.06) = 0.3$  N m.

This moment enacts a normal (pulling) stress  $\sigma$  that changes linearly in magnitude, from zero at the anterior of the suction disk, to a maximum value at the posterior end of the disk. The value of this maximal stress can be calculated by standard solid mechanics techniques as

$$\sigma = \frac{My}{I} \tag{3}$$

where  $y$  is the distance from the disk's center to any other point on the disk, and  $I$  is the moment of inertia (= second moment of the area) of the disk shape. We take this to be roughly elliptical, so that

$$I = \frac{\pi w b^3}{4} \tag{4}$$

where  $w$  is the disk half-width ( $w = 0.017$  m nominal), and  $b$  is the disk half-length ( $b = 0.04$  m nominal).

Combining equations (2), (3), and (4), the stress is given by

$$\sigma = \frac{4m \omega_d^2 R d y}{\pi w b^3} = \frac{4M y}{\pi w b^3} \quad (5)$$

The maximal  $\sigma$  occurs at the disk's edge, a distance  $y = 0.04$  m from the center. With the nominal values used in equation (5),  $\sigma = 14.2 \times 10^3$  Pa.

$$\sigma = \frac{(4)(0.3)(0.04)}{\pi(0.017)(0.04)} = 1.4 \times 10^4 \text{ Pa} \quad (5)$$

To see whether such a pulling stress can cause the beginning of separation, we need to return to the measured total force required for separation, which depends on the surface (Perspex or sharkskin). Taking the worst case of 20 N for sharkskin, this results in an average stress of

$$\sigma = \frac{\text{force}}{\text{area}} = \frac{F_c}{A} = \frac{F_c}{\pi w b} = \frac{20}{\pi(0.017)(0.04)} = 9.3 \times 10^3 \text{ Pa} \quad (5)$$

*i.e.*, less than the maximum achievable stress. From equation (5) stress required for peeling is achieved for a rotation rate of

$$\omega_d = \left[ \frac{\pi \sigma w b^3}{4m R d y} \right]^{1/2} = \left[ \frac{\pi(9.3 \times 10^3)(0.017)(0.04)^3}{4(0.1)(0.14)(0.06)(0.04)} \right]^{1/2} = 1.3 \text{ rad/s} \quad (6)$$

This value of  $\omega_d$  corresponds to a frequency of 2.4 Hz. For the sharksucker, the separation rate is 10.0 rad/s, or 1.6 Hz; whereas for the whalesucker,  $\omega_d$  is 16.9 rad/s, or approximately 2.7 Hz. All these values are well within the 3 Hz capability of spinner dolphins (Fish *et al.* 2006).

There exist additional reasons that drive spinner dolphins perform their aerial maneuvers. It has been proposed that aerial spins are a means of communication (Norris and Dohl 1980, Norris *et al.* 1994). By forcefully impacting the water surface, dolphins can indicate position, physical condition, and dominance. Although the model in this communication does not address these acoustic behaviors, results of the model indicate that remora dislodgement is possible.

The spinning may be a behavioral response to remora attachment necessitated by an inability to remove parasites by traditional mechanisms. The limited mobility of the limbs and reduced flexibility of the body negate parasite removal by biting, combing, scratching, and rubbing. Sharksuckers appear to irritate sharks and induce rotational and nonrotational behavioral patterns (Ritter and Godknecht 2000, Ritter 2002, Ritter and Brunnschweiler 2003, Carlson *et al.* 2004, Brunnschweiler 2005). Similarly, remoras would be irritating to a highly sensitive and naked skin, such as in dolphins (Kolchin and Bel'kovich 1973; Schwartz 1977; Ridgway and Carder 1990, 1993; F. E. Fish<sup>2</sup>).

The spin has multiple functions in remora dislodgement (Fig. 4). The spin reorients the remora on the dolphin body (Fish *et al.* 2006). The centrifugal force radially orients

<sup>2</sup> Personal observation from F. E. Fish, West Chester University, December 2004.

the unattached portion of the body. This results in a greater surface area exposed to the water on reentry and greater drag on the remora body on impact. The drag coefficient on the cylindrical body is 13 times the coefficient of the attached head (Hoerner 1965, Streeter 1966). As indicated in this analysis, the centrifugal force of the spin stresses the posterior edge of the suction disk. The stress would be sufficient to break the suction between the remora's disk and dolphin's body. Resistance to dislodgement would be reduced.

Although the centrifugal stresses that are required for detachment are produced by the dolphin spinning, the detachment probably takes longer than the time spent in the air, so that a *coup de grace* is required to make sure that the remora is completely separated at the end of the maneuver. This is provided by the fact that the dolphin lands broadside with the remora preferentially in a horizontal orientation, producing a large drag force on the partially detached remora. The lateral application of force is oriented parallel with the ridges of spines on the disk. This orientation makes it easier to dislodge the remora by a shearing action and reduces the grip of the spines.

As no data exist for sideways detachment of remoras, we need to rely on the calculation of the hydrodynamic force in Fish *et al.* (2006). This shows that if the reentry is timed right so that the remora is parallel to the water surface, the impact force may suffice to detach the remora by itself. A partially detached remora can, therefore, be easily separated even when the impact is at an arbitrary angle.

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